


Coarse Woody Debris Assay

in Northern Arizona Mixed-Conifer and Ponderosa Pine Forests

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Abstract

Coarse woody debris (CWD) provides important ecosystem services in forests and affects fire behavior, yet information on amounts and types of CWD typically is limited. To provide such information, we sampled logs and stumps in mixed-conifer and ponderosa pine (*Pinus ponderosa*) forests in north-central Arizona. Spatial variability was prominent for all CWD parameters. Correlations between amounts of CWD and current forest structure (tree density and basal area) were relatively weak. Most plots in mixed-conifer forest exceeded current USFS guidelines for retention of large logs. In contrast, 50% of ponderosa pine plots contained no large logs, and only 37% met current guidelines for log retention. Biomass of CWD in mixed-conifer forest typically fell within or above recommended levels for this forest type, whereas biomass of CWD in ponderosa pine forest typically fell within or below recommended levels. These results provide empirical data on amounts and types of CWD in this area and establish a baseline for monitoring CWD. The pronounced spatial variability in CWD parameters argues for managing CWD at broad spatial scales, rather than attempting to maintain average characteristics on every piece of ground.

Keywords: coarse woody debris, fuels, logs, mixed-conifer forest, ponderosa pine forest, stumps

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Introduction

Logs and stumps provide important sources of coarse woody debris (CWD) (Harmon and others 1986, McComb and Lindenmayer 1999). These structures help sustain populations of numerous fungi, lichens, vascular plants, and animals (e.g., Maser and Trappe 1984, Butts and McComb 2000, Bull 2002, Lee and Sturgess 2002, Torgersen 2002) and can affect fire behavior (Sackett 1979, Brewer 2008). Despite CWD's important contributions to ecological processes, information on amounts and especially types of CWD typically is limited. Existing information frequently results from fuels transects (Brown 1974) that provide only limited information on specific types of CWD present (Brewer 2008). Further, many CWD inventories do not consider standing stumps (USDA 2004: 3). Stumps can contribute importantly to overall amount and distribution of CWD and can provide important habitat components such as burrow, foraging, and perch sites for wildlife (fig. 1).

Figure 1. Examples of wildlife stump use. (A) Foraging sign at base of high stump; (B) Burrow located under stump; (C) Stump used as foraging perch by a Mexican spotted owl (*Strix occidentalis lucida*; photo by Todd A. Rawlinson).

Awareness of the general importance of CWD in forest planning and management has increased greatly in recent years (e.g., Bull and others 1997, Harmon 2001, Laudenslayer and others 2002, Torgersen 2002, Brewer 2008). Incorporating CWD in forest management will become more critical in southwestern mixed-conifer and ponderosa pine (*Pinus ponderosa*) forests in future years. Management emphasis in these fire-adapted forests focuses on reducing fuels and restoring more open forest structure through thinning and prescribed fire (Lynch and others 2000, Allen and others 2002, Peterson and others 2005). Prescribed fires typically burn many existing logs in these forests (Gordon 1996, Randall-Parker and Miller 2002, Innes and others 2006), although they also can create snags and logs (Horton and Mannan 1988, Fulé and Laughlin 2007, Roccaforte and others 2009). In addition, there is growing interest in using woody biomass from these forests to generate energy and produce wood products (Levan-Green and Livingston 2001, Neary and Zieroth 2007), which could reduce both current amounts and sources of future CWD. Finally, the amount and types of CWD strongly influence fire risk and behavior (Sackett 1979). For all of these reasons, empirical data on amounts and types of CWD are needed.

To provide such information, we sampled logs and stumps in mixed-conifer and ponderosa pine forests in north-central Arizona. We also sampled live trees to characterize stand structure in plots sampled. Here we (1) describe log and stump populations in these forest types, (2) evaluate potential relationships between stand structure and plot factors and CWD, (3) compare existing densities of large logs to standards for retention of large logs in these forest types (Reynolds and others 1992, USDA 1996), and (4) compare existing biomass of CWD to recommendations for biomass of CWD in these forest types (USDA 1999, Brown and others 2003). These data provide an initial assay of amounts and types of CWD in these forest types, provide preliminary information on factors potentially affecting amounts and types of CWD, and establish a baseline for monitoring changes in CWD.

Study Area

The study area encompassed approximately 73,000 ha in two National Forests in north-central Arizona (fig. 2). Within this area, study plots were randomly located in mixed-conifer and ponderosa pine forest (see Ganey 1999 for details on plot selection, location, and establishment). Mixed-conifer forests were dominated by Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and ponderosa pine. Other common species included limber pine (*P. flexilis*), Gambel oak (*Quercus gambelii*), and quaking aspen (*Populus tremuloides*). Ponderosa pine forest was dominated by ponderosa pine, but Gambel oak also was common and alligator juniper (*Juniperus deppeana*), Douglas-fir, quaking aspen, limber pine, pinyon pine (*P. edulis*), and Utah (*J. osteosperma*) and one-seed (*J. monosperma*) juniper were present in small numbers in some stands.

The study area included a wide range of topography and ecological conditions. The entire elevational range of these forest types within this area was represented, from the transition zone between pinyon-juniper woodland and ponderosa pine at lower elevations to the ecotone between mixed-conifer and Engelmann spruce (*Picea engelmanni*)–corkbark fir (*Abies lasiocarpa* var. *arizonica*) forests at higher elevations. In addition, plots ranged from intensively managed forests to administratively reserved lands such as wilderness and other roadless areas. We did not intentionally select plots in severely burned areas, but several plots were severely burned in recent wildfires. Consequently, these plots represent the range of variability well in these forest types.

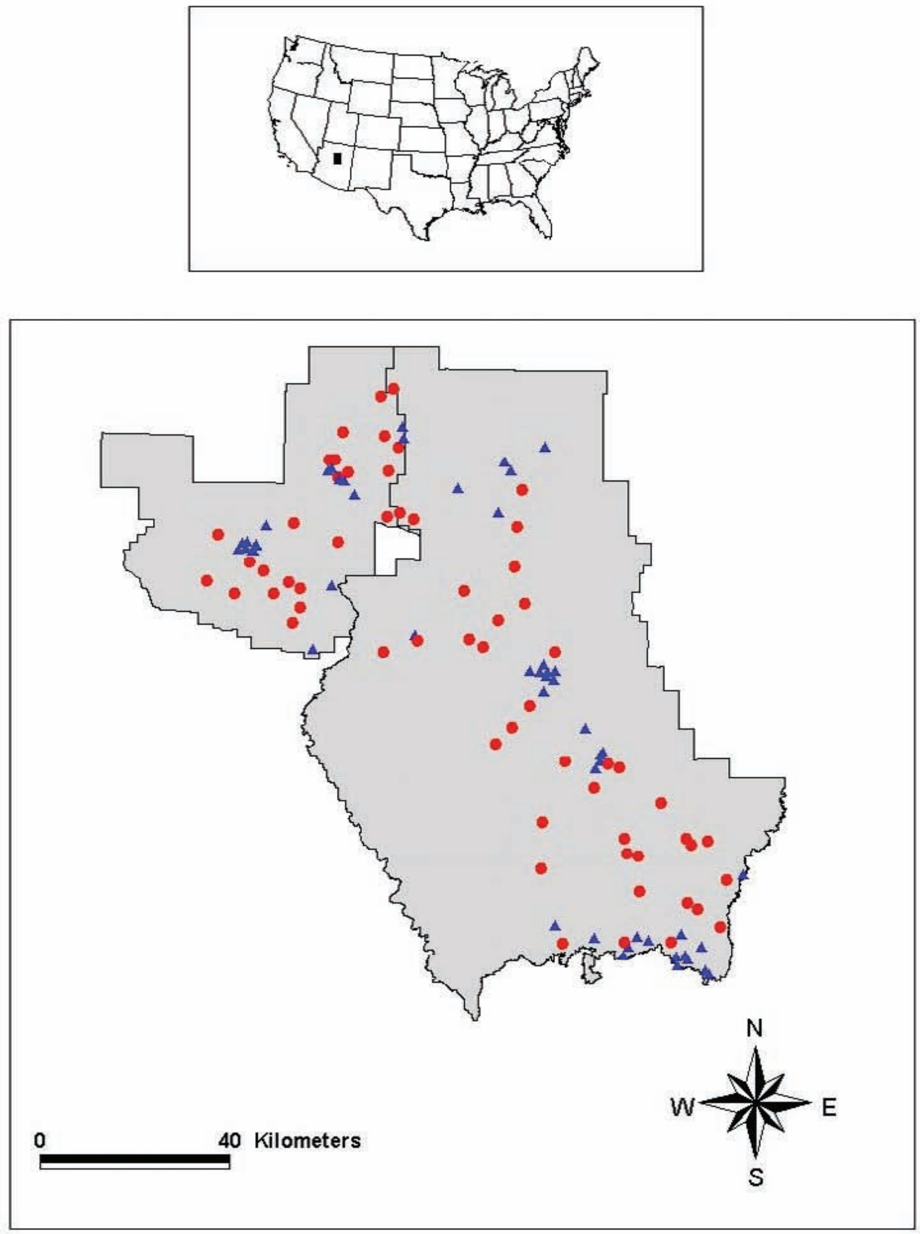

Figure 2. Location of the study area (black box, top) in northern Arizona, and locations of sampled plots within the study area (bottom). Plots were located in the Kaibab (left) and Coconino (right) National Forests. Plots in ponderosa pine forest (n = 60) are indicated by red circles, and plots in mixed-conifer forest (n = 53) are indicated by blue triangles.

Methods

Field Sampling

This study opportunistically utilized a series of permanent plots established in 1997 to monitor snag dynamics (*n* = 53 and 60 plots in mixed-conifer and ponderosa pine forest, respectively). The original plots were 1 ha each in area (100 by 100 m), but we sampled logs, stumps, and live trees in a 0.09-ha subplot (30 by 30 m) within each plot. We reduced plot size because logs, stumps, and trees were more abundant than snags, and time constraints precluded sampling these features on the entire 1-ha plot. Logs, stumps, and trees were sampled in 2004.

Plot-level characteristics recorded included forest type, timber status (logged or thinned versus unlogged), road access to plot (yes or no), and terrain (flat [≤10% slope], moderate [11-25% slope], or steep [>25% slope]).Within each plot, we sampled all logs ≥20 cm in large-end diameter and ≥2 m in length; all stumps ≥20 cm top diameter and <2 m in height; and all live trees ≥20 cm in diameter at breast height (dbh) and ≥2 m in height. The 20-cm minimum diameter was selected for consistency with the original snag monitoring study, which ignored smaller snags because they were suspected to be relatively unimportant to native wildlife. Thus, all logs and stumps sampled correspond to >1,000-hr fuels as defined by fuels managers (Maser et al 1979: table 25), but not all 1,000-hr fuels were sampled (i.e., pieces with large-end diameter >7.6 cm and <20 cm or with length <2 m were not sampled).

We uniquely marked all logs and stumps with numbered metal tags to facilitate tracking of individual structures in future re-inventories. For all logs, we recorded origination class (cut versus broken), large- and small-end diameter (nearest cm), length (nearest 0.1 m), and decay class. Parameters for length and diameter of logs referred to the portion of the log contained within plot boundaries, and only that portion of the log was sampled. Decay classes for logs (fig. 3) followed Parks and others (1997: 34-35). Class 1 logs retained most bark and branches, had little decay in the wood, and rested largely above ground, held up by existing branches. Class 2 logs were in contact with the ground, had lost some of their bark and branches, and had some decay in the wood. Class 3 represented logs that were no longer intact and had begun decomposing into the forest floor. These logs were extensively decayed and lacked both bark and limbs. Assignment to decay classes was subjective, but all sampling was done by the authors, and we cross-checked classification between ourselves to minimize variability between observers.

For all stumps, we recorded origination class (cut or broken), diameter (nearest cm), stump height (nearest 0.1 m), and decay class. We measured diameter across the top of the stump; for stumps that were markedly non-round, we took two perpendicular measures and averaged them. We recognized five decay classes for stumps, with higher numbers indicating older stumps (fig. 4). Class 1 stumps were freshly cut or broken, with sap still present, bark intact, and original wood color retained. Class 2 stumps retained bark and had exposed surfaces that were still flat and smooth, but the exposed wood had turned gray. Class 3 stumps were older, with loose bark, exposed surfaces beginning to round, and gray exposed wood. Class 4 stumps generally lacked bark, with wood decaying and few or no flat portions remaining in the exposed surface. Class 5 stumps were decomposing, with rounded surfaces.

We recorded species and dbh (nearest cm) of all live trees.


(A)


(B)


(C)

Figure 3. Decay classes recognized for logs. (A) Decay class 1; (B) Decay class 2; (C) Decay class 3. Decay classes are described in the text.

(A)

(B)

(C)

(D)

(E)

Figure 4. Decay classes recognized for stumps. (A) Decay class 1; (B) Decay class 2; (C) Decay class 3; (D) Decay class 4; (E) Decay class 5. Decay classes are described in the text.

Data Analysis

We estimated log and stump volume based on mean diameter (calculated for logs as: [large-end diameter + small-end diameter]/2) and length, and assuming cylindrical shape. We estimated basal area of live trees from dbh measurements.

Because species composition, stand density, disturbance regimes (Kaufmann and others 2007), and management guidelines for CWD (USDA 1996, 1999, Brown and others 2003) all differ between mixed-conifer and ponderosa pine forest, we expected amounts and types of CWD to differ between these forest types. Consequently, we were not interested in formally comparing estimates of CWD between forest types. We present some general comparisons between forest types for informational purposes, but summarized data are presented within forest type.

We present data for a number of different CWD parameters, including density, volume, area covered, total log length, and biomass, because managers have used all of these parameters in various contexts (Bull and others 1997). We focused most statistical analyses on estimates of volume because such estimates incorporate both number and size of CWD pieces and, therefore, provide more information than other parameters. We used number of logs or stumps rather than volume in summarizing size-class and decay-class distributions, however.

Because plots were selected randomly rather than stratified by levels of plot factors, sample sizes were small for some levels of main plot factors (table 1) and very small for some combinations of plot factors (e.g., unlogged ponderosa pine forest lacking road access in steep terrain). This greatly limited our ability to model CWD as a function of plot factors. Consequently, we conducted simple exploratory analyses within forest type by comparing log and stump volume across levels of main plot factors, using either Mann-Whitney or Kruskal-Wallis tests (Conover 1980), depending on the number of factor levels. We evaluated the strength of potential relationships between forest structure (tree density and basal area) and log and stump volume using Pearson's correlation coefficient. All measures of variability around means presented in the text are standard errors. We also present ranges for parameter estimates because variability in CWD parameters likely is as or more important than central tendency (e.g., Stephens 2004, Stephens and others 2007).

Table 1. Number and percent (in parentheses) of sample plots by forest type and levels of plot factors, northern Arizona, 2004.

		Forest type	
Factor	**Level**	**Mixed-conifer forest**	**Ponderosa pine forest**
Timber status			
	Logged	29 (54.7)	50 (83.3)
	Unlogged	24 (45.3)	10 (16.7)
Road access			
	Yes	16 (30.2)	33 (55.0)
	No	37 (69.8)	27 (45.0)
Terrain			
	Flat	3 (5.7)	33 (55.0)
	Moderate	24 (45.3)	24 (40.0)
	Steep	26 (49.0)	3 (5.0)

We estimated density of large logs (defined as ≥30.5 cm midpoint diameter and ≥2.44 m in length) by forest type and compared those estimates to U.S. Forest Service (USFS) management guidelines for retention of large logs in the Southwestern Region (Reynolds and others 1992, USDA 1996). We estimated biomass of logs and stumps using estimates of wood density from Brown and See (1981). We used their estimate for sound material (25 lbs/ft^3) for logs in decay class 1 and stumps in decay classes 1 and 2, their estimate for rotten material (19 lbs/ft^3) for logs in decay class 3 and stumps in decay classes 4 and 5, and an intermediate value (22 lbs/ft^3) for logs in decay class 2 and stumps in decay class 3. We compared the resulting estimates to recommendations for biomass of CWD in these forest types (USDA 1999, Brown and others 2003).

Results

Plot Characteristics

Relative to ponderosa pine plots, mixed-conifer plots were less likely to show evidence of recent logging or thinning, less likely to have road access to or adjacent to the plot, less likely to occur in flat terrain, and more likely to occur in steep terrain (table 1). Tree density ranged from 78 to 489 (mean = 274.8 ± 13.1) trees/ha in mixed-conifer forest and from 11 to 689 (mean = 237.6 ± 18.1) trees/ha in ponderosa pine forest; and basal area ranged from 7 to 52 (mean = 25.8 ± 1.4) and from 1 to 44 (mean = 20.8 ± 1.2) m^2/ha in mixed-conifer and ponderosa pine forest, respectively, illustrating the wide range in forest structural conditions sampled.

Mixed-Conifer Forest

Logs (n = 638) and stumps (n = 287) were present on 100 and 85%, respectively, of mixed-conifer plots. Most logs (93%) were classified as broken in origin, whereas 64% of stumps resulted from harvest activities in mixed-conifer forest. On average, CWD (logs and stumps combined) covered 261.2 ± 23.8 m^2/ha of ground area in mixed-conifer forest (or approximately 2.6% of total area), with area covered varying more than 30-fold among plots (range = 21.8–740 m^2/ha). Total length of logs averaged 895.6 ± 83.6 m/ha in mixed-conifer forest, and varied more than 20-fold across plots (range = 96.7–2583.3 m/ha).

Both log (mean = 68.5 ± 7.1, range = 1.0–191.4 m^3/ha) and stump (4.8 ± 0.7, range = 0–21.2 m^3/ha) volume also varied enormously across plots in mixed-conifer forest. Neither log nor stump volume was significantly correlated with either tree density or basal area in mixed-conifer forest (all P-values > 0.482).

Log volume did not differ between logged and unlogged plots in mixed-conifer forest (P = 0.480, see table 1 for sample sizes). In contrast, stump volume was significantly greater (P = 0.015) in logged plots (6.1 ± 1.0, range = 0–21.2 m^3/ha) than in unlogged plots (3.2 ± 0.7, range = 0–10.7 m^3/ha). This finding may seem self-evident, but recall that almost 36% of stumps were natural in origin in this forest type, and some of these stumps were large. Neither log nor stump volumes differed significantly between plots with and without road access in mixed-conifer forest (both P-values > 0.076). Stump volume declined significantly (P = 0.020) from flat to moderate terrain (6.6 ± 1.1, range = 0–21.2 m^3/ha) to steep terrain (2.9 ± 3.0, range = 0–10.7 m^3/ha), whereas log volume did not differ across terrain type in mixed-conifer forest (P = 0.712).

Density of both logs (133.8 ± 10.2, range = 11.1–311.1 logs/ha) and stumps (60.2 ± 9.1, range = 0–355.6 stumps/ha) also was highly variable across plots in mixed-conifer forest. Logs greatly outnumbered stumps in most plots and contributed approximately 69% of CWD density and 93% of CWD volume in this forest type.

Diameter distributions of logs and stumps differed from tree populations in mixed-conifer forest (fig. 5). Logs and especially stumps tended to be less common than trees in the smallest diameter classes and more common than trees in the largest diameter classes. Logs in later decay classes dominated log populations in mixed-conifer forest (fig. 6). Stump populations also were dominated by later decay classes (fig. 7), and class 1 stumps were absent in this forest type.

Density of large logs also was highly variable in mixed-conifer forest (range = 0–133.3 large logs/ha). Both mean (35.2 ± 4.5 logs/ha) and median (22.2 logs/ha) density of large logs exceeded current guidelines for retention of large logs (12.4 logs/ha) in mixed-conifer forest. Most plots (79.3%) in this forest type contained large logs, and 69.7% of all mixed-conifer plots met or exceeded the guideline.

Biomass of CWD averaged 25.8 ± 2.5 tonnes/ha in mixed-conifer forest and also was highly variable spatially (range = 1.7–71.1 tonnes/ha), with 20% of plots providing 43% of total biomass. Only 30.2% of mixed-conifer plots fell within the range for CWD biomass recommended for this region by USDA (1999; ~18 to 36 tonnes/ha or 8 to 16 tons/ac), with 39.6% falling below these levels and 30.2% exceeding recommended levels. In contrast, 58.5% of ponderosa pine plots fell within "optimum" levels of CWD recommended for warm, dry forest types in general (~11 to 45 tonnes/ha or 5 to 20 tons/ac; Brown and others 2003: figure 2); 26.4% fell below these recommended levels; and only 15.1% exceeded these recommended levels.

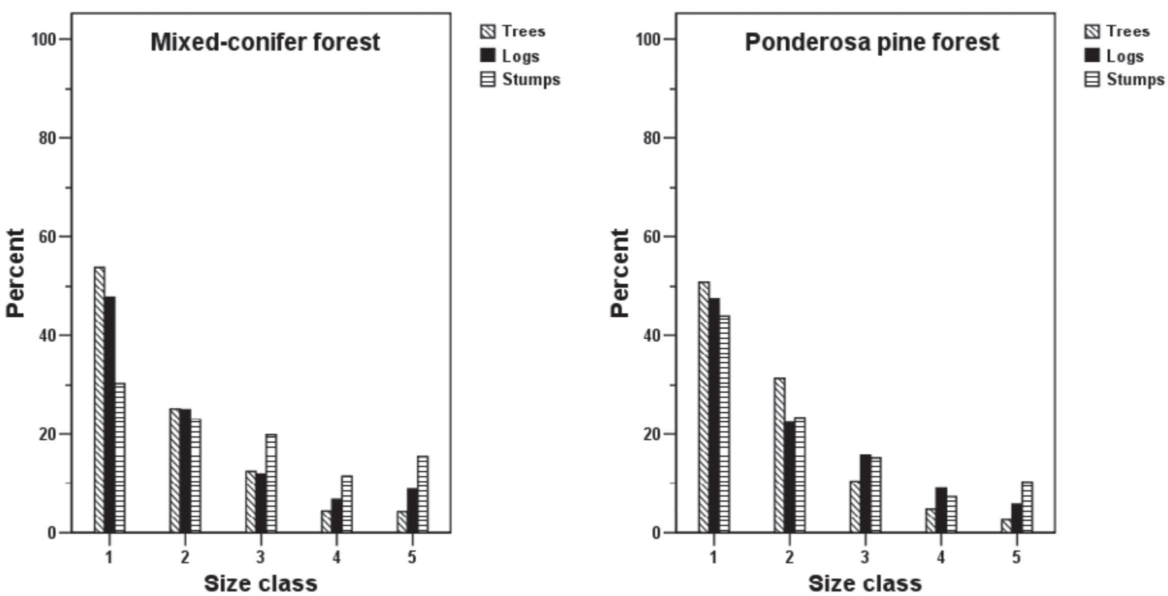

Figure 5. Diameter distributions of live trees, logs, and stumps in mixed-conifer (left) and ponderosa pine (right) forest, northern Arizona, 2004, based on samples of 53 and 60 plots in mixed-conifer and ponderosa pine forest, respectively. Percentages of trees, logs, and stumps by size class are shown. Size classes (diameter) are: 1 = <30 cm, 2 = 30–39.5 cm, 3 = 40–49.5 cm, 4 = 50–59.5 cm, and 5 = >59.5 cm. Structures were assigned to size classes based on diameter at breast height (trees), large-end diameter (logs), or top diameter (stumps). Sample sizes are: 1,327 trees, 638 logs, and 287 stumps in mixed-conifer forest and 1,267 trees, 224 logs, and 411 stumps in ponderosa pine forest.

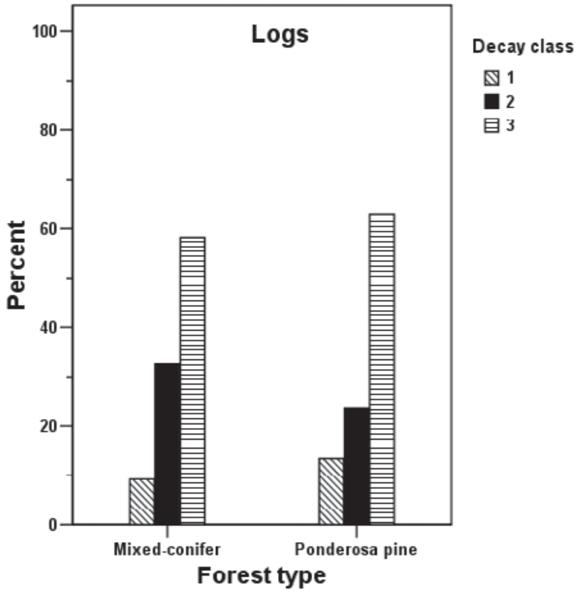

Figure 6. Decay-class composition (%) of logs in mixed-conifer (*n* = 638 logs) and ponderosa pine (*n* = 224 logs) forest, northern Arizona, 2004, based on samples of 53 and 60 plots in mixed-conifer and ponderosa pine forest, respectively. Decay classes are described in text.

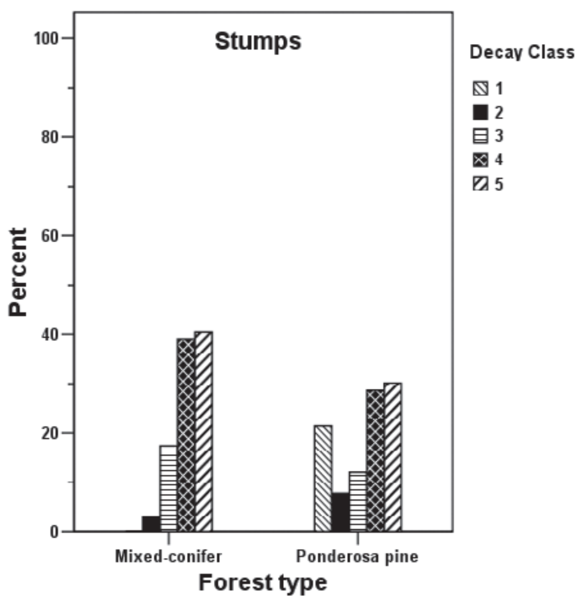

Figure 7. Decay-class composition (%) of stumps in mixed-conifer (*n* = 287 stumps) and ponderosa pine (*n* = 411 stumps) forest, northern Arizona, 2004, based on samples of 53 and 60 plots in mixed-conifer and ponderosa pine forest, respectively. Decay classes are described in text.

Ponderosa Pine Forest

Logs (n = 224) and stumps (n = 411) were each present on 81.7% of ponderosa pine plots. Only two ponderosa pine plots (3.3%) lacked both logs and stumps. As in mixed-conifer forest, most logs (81%) were classified as broken in origin. In contrast, 91.5% of stumps in ponderosa pine forest resulted from harvest activities. Amount of ground area covered by CWD varied widely among plots (74.5 ± 11.1, range = 0–438.9 m^2/ha; or approximately 0.7% of total area), as did total length of logs (241.1 ± 36.3, range = 0–1326.7 m/ha).

As in mixed-conifer forest, both log (52. 2 ± 21.1, range = 1.0–191. 4 m^3/ha) and stump (3.1 ± 0.4, range = 0–11.4 m^3/ha) volume varied widely across plots in mixed-conifer forest. Log volume was weakly correlated with tree density in ponderosa pine forest (Pearson's r = 0.287, P = 0.026), but was not correlated with basal area (P = 0.108). Stump volume was not correlated with either tree density or basal area in ponderosa pine forest (both P-values > 0.222).

Log volume did not differ between logged and unlogged plots or between plots with and without road access in ponderosa pine forest (all P-values > 0.090, see table 1 for sample sizes). In contrast, stump volume was significantly greater on logged (3.5 ± 0.4, range = 0–11.4 m^3/ha) than on unlogged plots (1.1 ± 0.5, range = 0–4.2 m^3/ha; P = 0.003) and on plots with road access (4.0 ± 0.5, range = 0–11.4 m^3/ha versus 2.0 ± 0.4, range = 0-6.5 m^3/ha in plots lacking road access; P = 0.005). Stump volume did not differ across terrain levels (P = 0.198), but log volume increased with terrain steepness (9.4 ± 2.9, 24.1 ± 5.8, and 42.4 ± 25.9 m^3/ha in flat, moderate, and steep terrain, respectively; P = 0.002).

Density of logs (41.5 ± 5.7, range = 0–222.2 logs/ha) and stumps (76.1 ± 12.4, range = 0–444.4 stumps/ha) also varied widely across plots in ponderosa pine forest. Unlike mixed-conifer forest, however, stumps frequently outnumbered logs in ponderosa pine forest and contributed approximately 65 and 15% of total CWD density and volume in ponderosa pine forest.

As in mixed-conifer forest, diameter distributions of logs and stumps differed from tree populations in ponderosa pine forest (fig. 5). Again, logs and especially stumps tended to be less common than trees in the smallest diameter classes and more common than trees in the largest diameter classes, although this trend was less pronounced in this forest type. Logs in later decay classes dominated log populations in ponderosa pine forest (fig. 6). Stump populations in ponderosa pine forest also contained relatively high proportions of stumps in the two latest decay classes, but class 1 stumps also were well represented in ponderosa pine forest (fig. 7).

Large logs were sparsely distributed in ponderosa pine forest. Mean density of large logs (9.8 ± 2.7, range = 0–111.1 logs/ha) exceeded the target for retention (7.4 logs/ha) in this forest type, but this parameter was greatly influenced by high numbers of large logs in only four plots. Median density of large logs in this forest type was zero, and only 36.7% of ponderosa pine plots met or exceeded the guideline for retention.

CWD biomass averaged 7.0 ± 1.2 tonnes/ha in ponderosa pine forest, and spatial variability again was relatively pronounced (range = 0– 45.0 tonnes/ha), with only 20% of plots providing 63% of total biomass. Ninety percent of ponderosa pine plots fell below levels for CWD recommended by USDA (1999), and only one plot exceeded the recommended levels. Most plots (78.7%) also fell below "optimum" levels of coarse woody debris recommended for warm, dry forest types in general (Brown and others 2003: fig. 2); and no plots exceeded these levels.

Discussion

Coarse woody debris was well distributed across the landscape in both forest types. Spatial variability in amount of CWD was considerable but still lower than variability in Jeffrey pine (*P. jeffreyi*)–mixed-conifer forests studied in the Sierra San Pedro Martir of Baja California, Mexico (Stephens 2004, Stephens and others 2007). In that area, 37% of plots had no 1,000 hr fuels, versus only 1.8% of our plots, and 75% of the 1,000-hr fuels occurred on only 20% of the plots (versus 43 and 63% of CWD in this study by forest type; see above). Stephens (2004, see also Stephens and others 2007) hypothesized that the large spatial variability in the Sierra San Pedro Martir resulted from an intact, frequent surface fire regime that maintained a patchy distribution of fuels. We suspect that disruption of surface fires in our study area has resulted in a more continuous distribution of forest fuels than occurred under historical conditions (see also Skinner 2002).

Amounts of CWD were not strongly linked to current stand structure in these forest types. However, road access, terrain, and past harvest activities appeared to affect CWD volume, especially stump volume. Differences between areas with and without recent thinning are primarily related to effects of those management treatments. In contrast, lower stump volumes in areas lacking road access and/or areas of steep terrain likely reflect lower levels of human access. For example, Wisdom and Bate (2008) documented significant reductions in densities of snags, which serve as sources of CWD, related to both human access and harvest intensity.

Relative contributions of logs and stumps to CWD varied between forest types. Stumps contributed over 65% of CWD density and 15% of CWD volume in ponderosa pine forest. Stumps appeared less important in mixed-conifer forest but still contributed 31% of CWD density. This suggests that inventories that do not include standing stumps are ignoring an important source of CWD in these forest types, particularly in managed stands.

Comparative data on CWD in these forest types are sparse. Area covered by CWD in this study was relatively low in both forest types, but generally bracketed reported values from Jeffrey pine–mixed-conifer forest in the Sierra San Pedro Martir, Mexico (1.5 ± 0.2%; Stephens and others 2007: table 2) and two ponderosa pine sites in Oregon and northern California (1.5 ± 0.2 and 2.2 ± 0.4%; Youngblood and others 2004: table 2). Observed log densities in Arizona were considerably lower than mean densities (approximately 219–230 logs/ha in mixed-conifer forest and 100–154 logs/ha in ponderosa pine forest, respectively) observed in similar forest types in northeastern Oregon (from Bull and Holthausen 1993, Torgersen and Bull 1995, and Torgersen 1997 as cited in Bull and others 1997:38; Youngblood and others 2004). Observed stump densities also were considerably lower than mean stump densities in ponderosa pine forests at Grand Canyon, Arizona (141.2 ± 34.8 stumps/ha, Fulé and others 2002). Many of the data on log density from Oregon represent late-successional or old-growth stands, however, which typically (but not always; see Kaufmann and others 2007) contain relatively large numbers of logs. In contrast, our data represent a wide range of successional stages. Further, sampling methodology and spatial scale likely differed among studies. For example, Fulé and others (2002) sampled smaller stumps, and this likely explains much of their increased stump density. Direct comparisons between regions and studies are difficult due to the paucity of comparative data, which reinforces the need for empirical data on amounts and types of CWD.

Tree populations were more skewed toward smaller size classes than either log or stump populations in these forest types (fig. 5). This could reflect differences in residence times for logs and stumps of different sizes (presumably large logs and stumps last longer than small logs and stumps; see Ganey and Vojta [2005] for similar results relative to snags in these same plots), discrepancies between past and current stand structure (relatively greater proportions of large trees historically, due to frequent fires; Covington and others 1994, Fulé and others 2003, Stephens and others 2009), past harvest patterns (especially for stumps), or combinations of these factors. Future inventories (planned at 5-yr intervals) will provide data on residence times useful in modeling these relationships.

Decay class distributions were dominated by logs and stumps in the later decay classes in both forest types (figs. 6 and 7), and Youngblood and others (2004: fig. 11) reported similar results from two ponderosa pine sites in central Oregon. These forest types historically experienced relatively frequent surface fire (Covington and others 1994, Skinner 2002, Fulé and others 2003, Stephens and Fulé 2005, Kaufmann and others 2007). These fires presumably burned many logs and stumps when they occurred (e.g., Gordon 1996, Randall-Parker and Miller 2002, Skinner 2002, Kaufmann and others 2007) but also created snags that provided a source of future logs (Horton and Mannan 1988, Fulé and Laughlin 2007, Roccaforte and others 2009). Thus, dynamics of log and stump populations in these forest types likely was driven more by fire than by decay dynamics (Skinner 2002, Kaufmann and others 2007, Stephens and others 2007, Brewer 2008), and large logs may decay slowly over long time periods in these forest types in the absence of fire. However, Stephens (2004, see also Stephens and others 2007) reported that 81% of fuels in a Jeffrey pine/mixed-conifer forest subject to frequent surface fires also were from rotten material. Thus, the role of fire in structuring decay distributions of CWD remains unclear.

Regardless of the reasons underlying observed decay-class distributions, those distributions have implications for fuels managers. Rotten woody material is easily consumed by fire under dry conditions, readily produces fire brands that contribute to torching and spotting activity in fires, and provides receptive ignition sites for brands produced elsewhere (Sackett 1979, Stephens and others 2007). Thus, the large numbers of rotten logs and stumps will pose challenges for fuels managers charged with reintroducing prescribed fire in these forest types.

Most mixed-conifer plots met or exceeded USFS guidelines for retention of large logs. In contrast, large logs were sparse and patchily distributed in ponderosa pine forest, with 50% of plots lacking large logs entirely. This suggests a need to emphasize retention of large trees and snags in ponderosa pine forest to provide future sources of large logs.

Estimated values for fuel loads in these forest types generally fell within the range of values reported previously for mixed-conifer (21.5–62 tonnes/ha; Sackett 1979, Brown and See 1981, Knapp and others 2005, Stephens and Moghaddas 2005) and ponderosa pine forest (3–23.2 tonnes/ha; Sackett 1979, Brown and See 1981, Robertson and Bower 1999, Stephens 2004, Stephens and others 2007). Many mixed-conifer plots fell within recommended ranges for biomass of CWD (USDA 1999, Brown and others 2003), but a substantial proportion fell above recommended levels. In contrast, most ponderosa pine plots fell below recommended levels. Again, direct comparisons are difficult here due to differences in sampling methods and size and types of CWD measured. Nevertheless, these data suggest that, despite years of fire suppression and many missed fire cycles in ponderosa pine forests, fuel loads frequently remain within or below recommended limits in this forest type. Passovoy and Fulé (2006: fig. 6) also reported that observed fuel loads generally remained within recommended limits even in severely burned ponderosa pine forests. In contrast, fuel loads in many mixed-conifer plots already exceed recommended levels, despite the fact that fewer fire cycles have been missed in this forest type. Stephens (2004, see also Stephens and others 2007) attributed this to the higher productivity of mixed-conifer forests and the resulting potential for rapid structural change.

We offer three caveats relative to "acceptable" fuel loads, however. First, Brewer (2008) noted that recommended levels of fuels are acceptable only where stand structure is consistent with structure that existed when natural fire regimes operated. In many cases, current stands have greater tree densities and more homogeneous and continuous canopies than historical stands in these forest types (Covington and others 1994, Fulé and others 2003, Stephens and Gill 2005), and CWD may be more continuously distributed as well (Stephens 2004, Stephens and others 2007). Under these conditions, fire can be difficult to control even when fuels are within recommended ranges. Second, we are witnessing a large pulse of drought-mediated tree mortality in these forests (Ganey and Vojta 2005, USDA 2008, Negron and others 2009). As the snags created break and/or fall, this will add considerable CWD to these forests, which may push CWD biomass above recommended levels. Third, this elevated tree mortality may not be a short-term phenomenon. Considerable climate-related mortality is occurring in and beyond western forests (e.g., van Mantgem and Stephenson 2007, van Mantgem and others 2009, Allen and others 2010). Coupled with model predictions suggesting increasingly warmer and drier climate in the southwest (e.g. Seager and others 2007), this suggests a possibility for rapid and potentially large increases in fuel loads in southwestern forests. All of these factors suggest a need for monitoring trend in amounts and kinds of CWD in these forests.

Conclusions

The data presented here provide both an assay of current amounts and types of CWD and a baseline for future monitoring of CWD dynamics. Clearly, however, much additional information will be required to effectively manage CWD in the face of changing climates, disturbance regimes, and management paradigms (e.g., Millar and others 2007). Information on residence time of various species, sizes, and decay classes of logs and stumps will be required even to understand current patterns and their causes, let alone to predict future patterns. Present targets for management of CWD typically are based either on perceived wildlife habitat requirements or on acceptable fuel loads. These different types of targets may not always be in agreement or directly compatible with each other. For example, fuel loads typically are estimated by fuel inventories that may not provide information on the types and spatial distribution of CWD structures necessary to evaluate wildlife habitat (Bull and others 1997), and meeting wildlife targets may require retaining levels of CWD that fuels managers view as unacceptable. Further, there are, at present, numerous parameters estimated to describe CWD, including (at least) density, volume, biomass, log length, and percent area covered (Bull and others 1997). Each of these parameters has distinct advantages in particular situations, and there is no general consensus on which parameter or parameters have the greatest general applicability. For example, general wildlife targets may rely on estimates of density by structure type, whereas fuels managers may rely on biomass estimates.

Standardizing methods, targets, and parameters estimated would have obvious benefits in terms of communication across disciplines, but it may prove difficult because of the different objectives involved.

It also would be desirable to begin evaluating empirical data on CWD at larger spatial scales. Data from the Forest Inventory and Analysis National Program (http://fia.fs.fed.us/) may provide opportunities to conduct landscape-scale assessments of amounts and types of CWD present. Such large-scale assessments should become more important as managers increasingly begin planning at broader spatial scales. Finally, planners should recognize the inherent spatial variability in CWD (Stephens 2004, Stephens and others 2007, this study) and incorporate such variability in targets and/or planning efforts. This variability again argues for large-scale assessments, as well as for focusing management guidelines at broad scales rather than attempting to manage for average characteristics on every acre (Stephens 2004, Stephens and others 2007).

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